Optimum Throughput Rate under Buyer's Market in Capital Intensive Manufacturing Industry

Yunjung Suh, Yujin Bae, and Jaewoo Chung

***Abstract*—This study develops an economic model to find the optimum throughput rate that maximizes the profit with considering product price decline and the fixed cost based on a queuing theory in capital intensive manufacturing industry (CIMI). Comparing to the previous studies, the model reflects more realistic situations of which inventory levels vary over sales periods depending throughput rates. Through a set of simulation experiments, the paper draws an operating curve that maximizes the profit when a price decline rate, throughput rate, and inventory holding cost are given as inputs. By Simply applying the estimated price decline rate, throughput with cycle-time, and inventory holding cost in the model, one can calculate the future profit and use it in many decision-making applications.**

***Index Terms*—Inventory level, production optimization, price decline rate, product life-cycle, throughput rate.**

I. Introduction

Capital intensive manufacturing industry (CIMI) is an industry that requires a large amount of investments to produce goods such as semiconductor/LCD, oil refinery, steel industry, and airline industry. For an example, reference [1] shows that a new LCD fabrication facility requires multi-billion dollars due to very expensive fabrication toolsets and ultra-clean fabrication facilities. The one of the unique characteristics of CIMI is very high portion of fixed cost out of the total production cost. The industry generally operates its production facility 24 hours a day, 365 days a year. Since the unit price decreases as throughput increases due to the economies of scale, the throughput is conventionally the most important criterion to operate CIMI.

There have been intensive efforts to enhance throughput of CIMI. Logistic Operating Curve (LOC) based on queuing theory explains the relationship between throughput and cycle-time as illustrated in Fig. 1 as [2]. The cycle-time approaches to infinity as the throughput increases its theoretical maximum. The longer cycle-time requires not only the longer delivery time but also the higher inventory hold cost. The practical throughput is less than the ideal throughput due to disturbances in production lines. The LOC gives a proximate reference to determine the inventory level and cycle-time as [3].

The firms in the industry generally use relatively high WIP strategy to increase the throughput and to reduce the fixed cost; however, CIMI under buyer's market often suffers from the depreciation of inventory values due to the high throughput and inventory. High throughput will cause longer cycle-time which means late delivery and poor responsiveness to the customer. Also increased WIP and cycle-time will slow down the speed of production and decrease overall competitiveness of the line. As a result, sales will decline and firms will eventually lose market share. Therefore, an appropriate level of throughput, WIP, and cycle-time depending on the market situation should be maintained to remain in the market.

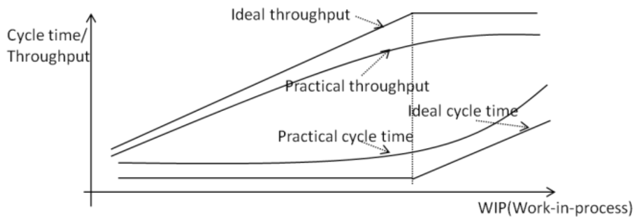

Fig. 1. Logistic operating curve (LOC) [3].

Under buyer's market in CIMI what is an appropriate throughput level? Conventionally it is answered by LOC as [3], [4]. However, if prices of goods drop significantly over time under buyer's market, the LOC cannot capture the drops effectively. Based on DRAMeXchange's analysis, the price of 128GB SSDs drops significantly and shrinks from $130 to less than $30 in 2016 as shown in Fig. 2 as [5]. Maintaining high throughput to reduce fixed cost will cause very high inventory level and falling the value of the inventory on the manufacturing facility. Inversely, if throughput drops too much, the firms will suffer from longer ROI (return on investment) due to huge investment.

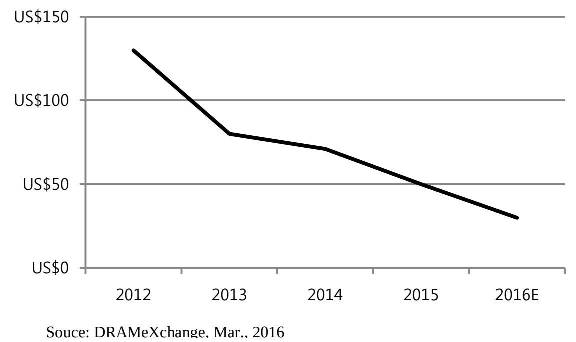

Fig. 2. 128GB SSD price trends [5].

Under buyer's market, though a manufacturing firm experiences losses in revenue, it often provides a good opportunity to expand its market share. Thus it is important to increase production speed for enhancing the responsiveness to the customers. In addition to obtain a chance of expanding

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the market share by increasing the number of products offered rather than increasing throughput is required. Therefore, increasing the speed of production and offering variable products while maintaining an appropriate level of throughput would be helpful as [6].

This study focuses on the total profit that varies throughput level and price degradation level. The changes of the throughput level affects many other cost factors such as cycle-time and WIP level. To weigh this phenomenon efficiently, the authors of the paper closely examine the values of inventory over time depending on a throughput level based on LOC. This study considers a realistic condition that the period of time from the production to sales. Previous studies are assuming that every product is sold right after the production is completed but this study reflects the fact that there is a certain time needed to be sold. The study applies this model for the semiconductor/LCD industry because it is one of the representatives of the CIMI.

This paper organized as follows. First, the paper proposes theoretical background for the economic model which is concerning price decline rate and inventory holding costs in section II. The model is introduced to evaluate the most profitable throughput level in section III. Section IV explains the simulation results of the model and avenues for future research on the topic are discussed.

II. Theoretical Background

In the academic field of production management, many previous studies note that the price of products declines very quickly. Leachman and Ding in [7] develop a model to quantitatively assess revenue gains resulting from increased speed of engineering and manufacturing execution. They quantify the value of cycle-time reduction when prices of goods go down. Weber and Fayed in [4] optimize throughput and cycle-time under price decays based on LOC with the addition of Leachman and Ding in [7]'s model. The fab operating curve developed in their model has identified preferred domains of fab performance. And the paper reveals that significant revenue and profit can be generated by extending the lean and value driven approach to managing the operating curve. But they fail to capture the increase of holding cost when throughput goes up. Also these studies assume that all the products were sold right after the production that they were not reflecting the realistic condition that requires inventory holding periods and price declines.

On the other hand, many studies have been done to examine inventory holding cost which is used to correspond with the customer demand variability, the expected service level, and the production variability. However, excessive inventory can cause serious profit loss due to the decay of inventory value and increased operating cost. Azzi *et al.* in [8] measure inventory holding cost with a multi-case study in warehouse investment decisions. They offered frameworks for measuring inventory holding cost precisely. Roy in [9] proposes an inventory model for deteriorating items with price dependent demand and time varying holding cost. And his research assumes that there is linearly increasing holding cost over periods.

From the research review, few studies have focused on decreasing values of WIP which can be inventory holding cost under price degradation. Also most of studies couldn't reflect the realistic condition that every product is not sold right after the production completed. Therefore, this study applies the realistic condition which considers the period of time from the production to sales. This study developed an economic model to optimize throughput levels and production speed (cycle-time) for CIMI focusing on inventory holding cost and price decline rate.

III. Development of Economic Model

We assume that a new product "*k*" is initially introduced into a fab (started at the beginning of the line) at time $t = 0$, continues to be started at a variable rate of wafers per unit time until the final wafer is started at a particular time, $t = \theta$, which is the lifecycle of a product *k*. Total fab throughput (Q_k) can vary over time and remain constant over the complete lifecycle of product *k*. N_k is the expected number of fully functional integrated circuits on a product wafer of *k*. K_k represents the unit price of a product *k* and the amount of time it takes for K_k to decrease by a factor of *a*. $a=-\ln(1-YPD)/365$ which is a daily decline rate and *YPD* is the yearly price drop (10%, 40%, 50%, 60%). CT_k is the average cycle-time of a wafer that was started at *t* and acts as a batch for product *k*. The cycle-time varies depending on the fab throughput which can be calculated by LOC. The total revenue (1) accrued from all wafers started over the lifecycle of product *k* is give by a variant of Leachman and Ding in [7], Weber and Fayed in [4]'s formula.

$$TR_k(\theta) = \sum_{t=0}^{\theta}\left[Q_k \cdot N_k \cdot K_k \cdot e^{-a_k(t+CT_k)}dt\right]. \tag{1}$$

To consider the period of time from the production to sales we assume that the demand ($D_k(t)$) is a integer and positive number which is expected as a bell-shape with mean (μ), $\theta/2$ and standard deviation (σ), $\theta/4$ as (2). By α, demand can be increased or decreased.

$$D_k(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left[(t-\mu)^2 / 2\sigma^2\right]} \times Q_{\max} \cdot N_k \cdot \alpha. \tag{2}$$

No wafers containing *k* exit the fab when $t < CT_k$ and there will be no revenue during that period of time. Wafers containing *k* exit the fab at a rate of Q_k over the time period $CT_k \le t \le \theta + CT_k$. The inventory at time *t* which is a integer and positive number can be the balance of the throughput at time *t* and the inventory at time *t-1* decreased by the demand at time *t* ($I(t) = I(t-1) + Q(t) - D(t)$). If the demand at time *t* is higher than the throughput (Q) and the inventory at time *t-1* ($I(t-1)$), the revenue at time *t* will be the same as the throughput with the inventory level at time *t-1*. If the demand at time *t* is lower than the throughput and the inventory at time *t-1*, the revenue at time *t* will be the same as the demand at time t. The total revenue considering demand can be as followed (3).

$$TR_k(\theta) = \sum_{t=0}^{\theta}[\min(Q_k \cdot N_k + I(t-1), D_k(t)) \times K_k \cdot e^{-a_k(t+CT_k)}]. \quad (3)$$

The total costs of fabricating product k that are accrued over the product's lifecycle can be calculated by fixed cost and the total costs of fabricating maximum throughput as [4], [10]. The fixed cost (F) is a fab construction cost which occurs once before the production of wafer for product k starts. The total costs of fabricating maximum throughput are the total costs of material used to produce wafers in a fully loaded fab which is known as constant $C(Q_{max})$. Through the total cost of ownership of the fab and wafer cost, calculate the cost of processing a wafer. The fab can take advantage of inverse linear economies of scale. The cost of a wafer is given by

$$C(Q_k) = C(Q_{max})[Q_{max} / Q_k]. \quad (4)$$

Processing cost per wafer per day can be linearly as wafers move through the fab and keep constant when fab throughput is kept constant over time as

$$WPC_k(Q_k) = C(Q_k) / CT_k. \quad (5)$$

The total costs of product k during the lifecycle can be calculated by the processing costs of fabricating throughput [4]. First, wafers containing product k are being started but none exit the fab until the cycle-time is passed ($0 \le t < CT_k$). Thus the total costs of this period can be calculated as the processing costs of fabricating maximum throughput during the cycle time. Next, wafers of product k exit the fab at the same rate that they are started ($CT_k \le t \le \theta$). The total costs of this period are constant as the sum of the total costs of fabricating maximum throughput until the product k's lifecycle ends. In this period, when demand is higher than the existing inventory with the throughput at time t, inventory holding cost will occur. Lastly, wafers containing product k are no longer being started but they still exit the fab until the cycle-time ($\theta \le t \le \theta + CT_k$). The total costs of fabricating product k are accrued over the product's lifecycle can be as followed (6).

$$\begin{aligned} &TC_k(\theta + CT_k) \\ &= F + \{\sum_{t=0}^{CT_k} Q_k \cdot WPC_k(Q_k) \cdot (t)\} \\ &+ \sum_{t=CT_k}^{\theta}(Q_k \cdot WPC_k(Q_k) \cdot CT_k) + \sum_{t=CT_k}^{\theta}(I(t) \cdot I_{\text{cost}\,t}) \\ &+ \sum_{t=\theta}^{\theta+CT_k}\{Q_k \cdot WPC_k(Q_k) \cdot (\theta + CT_k - t)\}. \end{aligned} \quad (6)$$

The total profit accumulated by product k over its lifecycle is given by

$$\begin{aligned} &TP_k(\theta + CT_k) \\ &= TR_k(\theta) - TC_k(t + CT_k). \end{aligned} \quad (7)$$

As shown in the figure, Fig. 3 compares the time window of research model with that of previous one. The model reflects the realistic condition that the period of time from production to sales by applying the inventory level according to the demand. The length of the time period varies depending on the throughput level based on queuing theory.

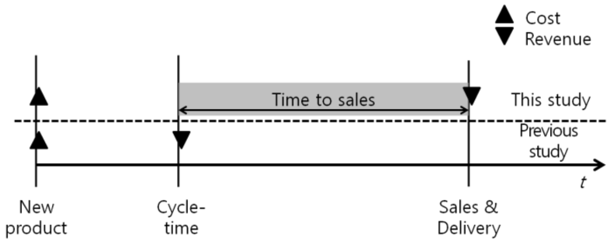

Fig. 3. Time window of the model.

IV. Simulation Results

In Table I we present hypothetical parameters for simulation experiments which were obtained from actual manufacturing site. The hypothetical fab has a maximum throughput of Q_{max} = 1000wpd. One wafer contains 200 instances of product k, 190 of which are expected to survive from the production process, i.e., the yield of a wafer, N_k = 190. A new product k is introduced into the fab at time t = 0 and the fixed cost (F_k) is $1 billion. The unit price K_k for product k is $50. The cost of a wafer is ($C(Q_{max})$) US$2000.

TABLE I: List of Parameters

Parameters	Value	Parameters	Value(US$)
Q_k / CT_k	900 wpd/16 days 920/18 940/23 960/32 980/60	I_{cost}	1 0.5 0.1 0.05
Q_{max}	1000 wpd	F_k	1 billion
θ	360 days 200 730 1095	K_k	50
YPD	0.1 0.4 0.5 0.6	$C(Q_{max})$	2000
N_k	190		
D_{max}	800000		

The change of cumulative profits according to incremental changes of throughput and cycle-time, inventory holding cost, product lifecycle, and yearly price decline rate is examined and analyzed. Fig. 4 describes the cumulative profits as a function of time at five different levels of throughput in lifecycle (θ_k) 3 years and yearly price decline rate of 10%. The cumulative profits of every throughput rate show linearly increasing. After 200 days, most of profits become positive and the lower throughput with shorter cycle-time gains positive profit relatively quicker. About 1 year later, the profits by most of throughputs show similar gains and after 500 days higher throughput makes higher profit. The highest profit is $4913 million achieved by 960 throughput with the inventory holding cost $0.5 and similar profits are lineally depicted by most of throughput rates. Although relatively low throughput with short cycle-time obtains profit quickly, high throughput makes more profit after 1year. The lifecycle of 3 years is long enough to make profits even for 980 throughput with the longest cycle-time of 60 days. Therefore, long lifecycle which can be interpreted as enough demand can compensate long cycle-time loss. Also if the lifecycle is longer than 2 years, high throughput is the best solution to achieve high profit.

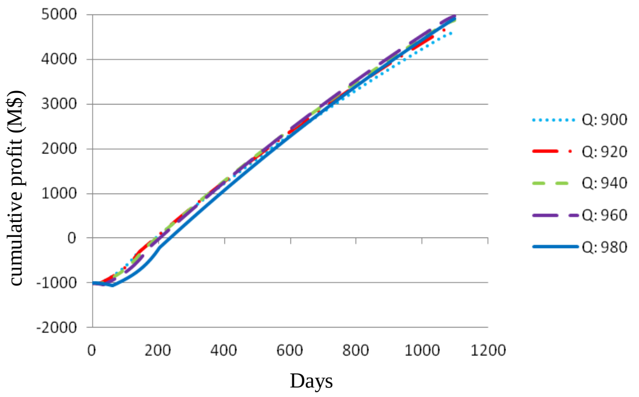

Fig. 4. Cumulative profits as a function of time at five different levels of throughput with lifecycle (θ_k) 3 years.

The cumulative profit difference by inventory holding costs is shown in Fig. 5. The results are after 1095 days and yearly price decline rate of 10%. When the inventory holding costs decrease, consequently the profits increase. The change of inventory cost from $1 to $0.5 brings about $127 million profit which is from $4836 to $4963 million by 960 throughput. In addition, the decrease of inventory holding cost to $0.1 brings the increase of the profit to $5064 million by 960 throughput. However, from the inventory holding costs of $0.05, the changes of profits become little as $5077 million. We can explain that the inventory holding cost of below $0.1 which is 0.02% of the product price would not impact on profit.

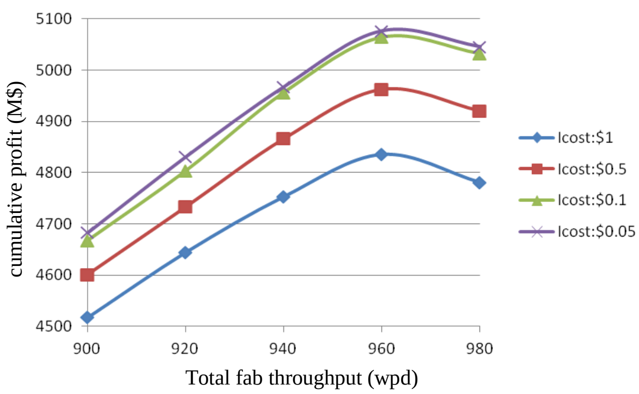

Fig. 5. The cumulative profit difference by the inventory holding costs.

Fig. 6 shows the cumulative profits of 3 years lifecycle product (θ_k = 1095) by 900 throughput with $1 inventory holding cost in three different price decline factors (*YPD*). When *YPD* increases from 40% to 50%, and to 60%, the cumulative profit after 3 years decreases from $1296 million to $447.9 million, and to -$304 million respectively. The profit of 40% *YPD* shows positive after 242 days and the highest profit of $1331 million is achieved at 1038 days. *YPD* with 50% begins to be positive profit after 273 days and decrease after 765 days from the highest profit of $644 million. 60% *YPD* becomes positive after 342 days and the highest profit of $174 million decreases after 578 days. The *YPD* rate gives major impact on profit, e.g., when *YPD* increases 10%, the highest profit decreases about $500 million and the profit start to decrease about 200 days earlier. 50% of *YPD* products should be sold within 800 days and *YPD* 60% within 600 days. Therefore, the product with highly fast decline price would have relatively high initial price to overcome the fast decline rate of product price. Also forecasting of *YPD* would help setting a product's lifecycle.

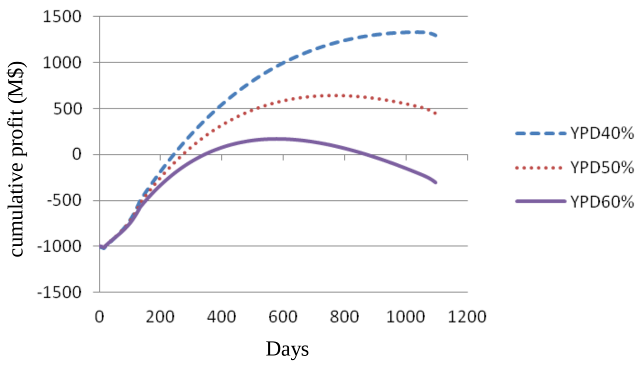

Fig. 6. The cumulative profit difference by the price decline rates (YPD).

The model examines and analyzes the change of cumulative profits according to incremental changes of throughput and cycle-time, inventory holding cost, product lifecycle, and yearly price decline rate. From the results of lifecycle and throughput differences show that most of profits become positive after 200 days and the profits by most of throughputs show similar gains about 1 year later. After 500 days higher throughput makes higher profit. Therefore, products lifecycle should be longer than 200 days to achieve high profits. Although relatively low throughput with short cycle-time obtains profit quickly, high throughput makes more profit after 500 days. The results of difference by inventory holding costs explain that the product's profit increases inverse proportional to the inventory holding costs. The inventory holding cost of below $0.1 which is 0.02% of the product price would not impact on profit. Thus firms should give an effort to reduce inventory holding cost with an automated cargo system and integrated inventory systems. The yearly price decline (*YPD*) factors give major impact on profit and give direction to decide the lifecycle of products. Therefore, the product with highly fast decline price should have shorter lifecycle and would have relatively high initial price to overcome the fast decline rate of product price.

High throughput causes long cycle-time and high inventory level. Moreover, product's price declines incrementally with serious impact on firms' profit. However, the products lifecycle can be decided to increase profits according to the price decline rate. For example, increasing demand with long product lifecycle can compensate firms' losses when the price decline rate is small. Longer than 2 years of lifecycle can enhance firms' productivity and profit. When the product's lifecycle is shorter than 1 year, maximizing throughput is not the best solution without reducing cycle-time and inventory level. Another solution is that reducing inventory holding cost as under 0.02% of product price which makes little difference in profit. Thus it is important to increase market share by increasing demand and products' lifecycle with product mix and product diversifying.

This study shows the importance of increasing market share rather than impudently increasing throughput level. Also the results would help firms increase profit with appropriate inventory cost, products' lifecycle, and throughput rate. By simply applying the estimated price decline rate, lifecycle, and inventory holding cost in the model, one can calculate the future profit and use it in many decision-making applications.

V. Conclusion

This study develops an economic model optimizing throughput levels and production speed (cycle-time) on the CIMI under buyer's market. The economic model is based on Logistic Operating Curve (LOC) under queuing theory and focused on inventory holding cost under price degradation. Comparing to the previous studies, the model reflects more realistic situations of which inventory levels vary over sales periods depending on throughput rates. Also the economic model analyzes the total cost under various business parameters such as product prices over time, fixed cost, cycle-times, inventory holding costs, and product lifecycle. Through a set of simulation experiments, the paper draws an operating curve that maximizes the profit when a price decline rate, throughput rate, and inventory holding cost are given as inputs.

There are many research efforts to find appropriate cycle-time (or WIP level) in CIMI but they fail to consider price deterioration which is very critical for some business environments such as semiconductor and LCD industry. This study will stress this academically and practically important problem. Because few studies have focused on the decreased WIP values with increased inventory level. This paper combines a cycle-time management problem with an inventory management problem to address a holistic view of production management. Two research streams are deeply studied by two different research groups but never have been discussed in the same table. Inventory management and cycle-time management are one of the critical decision making problem so that this study would contribute to improve existing theories for more efficient supply chain management. The results would provide useful insights to practitioners in those industries to expect the profit with various inputs.

The future study will include computational analysis to evaluate validity of analytical model with practical data from semiconductor or LCD industry. Longitudinal analysis of empirical research would show more significant results. Additional study of forecasts the unit sales price and demand will be required. The inventory holding cost with interest rate will also show effective analysis.

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